Ecological Modelling 385 (2018) 45–57

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Developing alternative forest spatial management plans when carbon and timber values are considered: A real case from northeastern China

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ARTICLE INFO

Keywords:
Forest management
Timber production
Carbon sequestration
Area restriction model
Green-up constraint
Carbon price

ABSTRACT

Forest ecosystems play an important role in mitigating global climate change, and this role has recently been further reinforced by the Paris Agreement. However, our knowledge with respect to the trade-offs between timber production and carbon sequestration in forest ecosystems is still seriously deficient. Therefore, the overall goal of this study is to quantitatively analyze the effects of a set of economic and ecological constraints on the joint production capacity for forest timber and carbon by alternative forest management strategies for a large forest in northeastern China. The proposed forest planning models integrate four alternative forest management strategies, namely, the timber-oriented management strategy (TMS), the carbon-oriented management strategy (CMS), the multiobjective management strategy (MMS), and the resource-restricted management strategy (RMS). Four different planning scenarios for each strategy were further generated by successively adding one additional constraint, which mainly included the even-flow of timber production, the adjacent constraints of harvest activities, and the minimum targets of carbon sequestration, over a 50-year planning horizon. The results showed that increasing the prices of carbon resulted in positive quadratic polynomial total and carbon net present values (NPVs), positive logistic carbon sequestration and stocks, and negative logistic harvest of timber and its NPV for optimal forest management plans, in which the carbon price of $100 per ton was a significant threshold for balancing the harvest of timber and carbon sequestration. In addition to the CMS, our tested spatial and nonspatial constraints all showed significant effects on optimal forest management plans when a realistic carbon price (i.e., $20 ton^{-1}) from the carbon trading market in China during 2014–2017 was employed, in which decreases of approximately 29.34% and 25.08% were observed for total NPV when twenty-percent deviations in harvest volume between any two consecutive periods were employed. Additionally, two periods of green-up constraints could further reduce the total NPV by approximately 17.87% and 15.73% for TMS and MMS, respectively, when compared with their base scenarios. However, increasing the minimum carbon target by one percent reduced the total NPV by approximately $29.44 per hectare per year when evaluated for RMS. Our optimization framework not only can be replicated in other regions with similar characteristics but also contributes to the ongoing debate about the trade-offs between carbon sequestration and wood production benefits.

1. Introduction

Forest management operations usually have significant effects on the structure and function of forest ecosystems. Therefore, there is an obvious need to model the effects of various forest management prescriptions on the evolution of forest ecosystems over time to choose optimal management alternatives. Forest management optimization can provide the most desirable forest plans (i.e., the temporal and spatial configuration of management actions) in terms of the global objectives and constraints of the entire forest enterprise; additionally, it can be used to quantitatively analyze the potential uncertainty and risk of complex forest decision-making processes, including forest inventory errors, growth prediction errors, the performance of various product markets, the preferences of decision makers, the unpredictability of natural hazards, and the effects of climatic changes (Pasalodos-Tato et al., 2013; Bettinger et al., 2013). In recent decades, public concerns about forest management have gradually transformed from traditional timber production goals to ecosystem-based services (e.g., carbon sequestration, biodiversity, wildlife habitat) and recreational (e.g., landscape aesthetics, oxygen production) values. However, the interactions

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https://doi.org/10.1016/j.ecolmodel.2018.07.009
Received 23 April 2018; Received in revised form 10 July 2018; Accepted 15 July 2018
Available online 20 July 2018

among these multitudinous goods and services of forest ecosystems can either be viewed as a trade-off or a synergy (Cademus et al., 2014), which are usually present in typical nonlinear relationships. Meanwhile, some additional nonlinear constraints are also necessary when other additional objectives are integrated, and the interactions between the objective and predefined spatial constraints are also ambiguous. Thus, considering more objectives may significantly increase the complexity of traditional harvest scheduling models, and analyses of these problems are also becoming more time consuming and resource demanding.

Recently, the role of forest ecosystems in mitigating global climatic changes has been further supported by the Paris Agreement (Framework Convention on Climate Change, 2015), which was approved by approximately 175 countries worldwide in 2015. Therefore, each country that ratified the Paris Agreement should implement appropriate policies and provide positive incentives for reducing emissions, for preventing deforestation and forest degradation, and for increasing the carbon stocks of forests (Framework Convention on Climate Change, 2015). However, the carbon benefits provided by forest ecosystems are generally considered to conflict with traditional timber production; thus, incorporating carbon objectives into the forest management planning process has created large challenges in forestry research and development. In recent years, some papers have successfully integrated carbon objectives into forest planning models. For example, Backéus et al. (2006), Bourque et al. (2007), Hennigar et al. (2008), Raymer et al. (2011) and Chen et al. (2011) incorporated carbon objectives into forest harvest scheduling models using traditional mathematical programming (i.e., linear programming, goal programming). Krcmar et al. (2005), Yousefpour and Hanewinkel (2009) and Baskent and Keles (2009) further incorporated other forest management objectives (e.g., biodiversity, water and oxygen) beyond timber and carbon benefits into forest planning models using linear programming. These studies have increased our knowledge of the trade-offs between timber production and carbon sequestration in forest ecosystems, but they focused only on nonspatial planning problems. Obviously, the specific management prescription implemented in any given management unit (or stand) may have significant effects on the adjacent units, e.g., the clear-cutting prescription of one stand may increase the risk of wind damage (Zeng et al., 2007; DuPont et al., 2015) or bark injury (Behjou, 2014) in a neighboring stand. Therefore, it is nearly impossible to simultaneously address several important social concerns in forest management practices without considering the spatial details.

Planning problems can usually be classified into two categories, i.e., spatial planning models and nonspatial planning models, based on whether they contain the necessary spatial information. Generally, nonspatial forest planning models are formulated with continuous variables (i.e., the percentage or hectares of a specific stand); in contrast, spatial forest planning models mostly focus on basic management units (or stands), in which the decision variables are typically represented by binary variables that can take only the values of 0 or 1. There are various ways in which forest harvest spatial constraints can be integrated into forest planning processes (McDill and Braze, 2000); however, the unit restriction model and the area restriction model are two of the most frequently used spatial constraint types in the forestry literature (Bettinger et al., 2002; Crowe and Nelson, 2005; Öhman, 2011; Tóth et al., 2013; Borges et al., 2015). These two approaches may be suitable for different planning problems (Murray, 1999), and selecting an approach mainly depends on the size of the stand relative to the maximum opening area. Generally, if the average size of the management units (or stands) across the forest landscape is similar to the maximum opening area, then two arbitrary neighboring units cannot be simultaneously harvested under the unit restriction model planning approach; however, in the area restriction model planning approach, two or more neighboring units can be harvested in the same period (or in adjacent periods) as long as their combined area does not exceed the maximum opening area (Murray, 1999). In fact, the unit restriction model can be treated as a special case of the area restriction model; thus, the area restriction model is typically a much more powerful and complex approach than the unit restriction model. The effects of various harvest adjacency constraints on a set of important forestry planning problems have been evaluated by several previous studies that mainly focused on forest economic and commodity production (Boston and Bettinger, 1999; Tóth et al., 2013), wildlife habitat preservation (Bettinger et al., 2002; Öhman, 2011), forest landscape maintenance (Baskent and Jordan, 2002), and water production (Baskent and Keles, 2009). The study by Dong et al. (2015a,b), to the best of our knowledge, is the only study that has included carbon benefits in the consideration of harvest adjacency constraints (i.e., area restriction model) in forest planning. However, Dong et al. (2015a,b) focused only on the results of a set of different age-class structures and did not consider the effects of various economic- and ecological-oriented forest management strategies on the carbon sequestration function of forest ecosystems.

The overall goal of this study is to quantitatively analyze the effects of a set of economic and ecological constraints on optimal management plans that include four alternative forest management strategies for a large forest in northeastern China. Our hypotheses were as follows: 1) a threshold carbon price might exist that affects the balance between harvesting timber and keeping trees to sequester carbon and 2) spatial constraints may have much larger effects than nonspatial constraints on joint economic profitability when forest timber and carbon objective are considered simultaneously. Therefore, the specific objectives are to 1) develop a spatially explicit forest management planning model that simultaneously considers carbon and timber benefits of forest ecosystems; 2) optimize the proposed planning model using a heuristic simulated annealing process; 3) analyze the sensitivity of the optimal management plan to various carbon prices; and 4) evaluate the effects of a set of economic and ecological constraints on the optimal management plans for the alternative forest management strategies. In all analyses, the results are presented and examined based on the amount and the net present value (NPV) of timber production and carbon sequestration over a planning horizon of 50 years.

2. Materials and methods

2.1. Case study area

The study area of Pangu Forest Farm is situated in Heilongjiang Province in the northeastern region of China (Fig. 1). The study area comprises an area of 123,423 ha, and approximately 96.72% of this area is subject to harvest scheduling. The remaining area is mainly composed of settlements, wetlands and mining areas. The forested area has 325 compartments and 6421 subcompartments (or stands) with an average size of 19.21 ha. Each stand has different species, ages, site qualities and stages of development. The forest contains coniferous and broadleaf species along with some forest openings. The main tree species are larch (*Larix gmelinii*) and birch (*Betula platyphylla*). Other species found in this area include *Pinus sylvestris*, *Picea asperata*, *Populus davidiana* and *Salix matsudana*. Of the total initial growing stock of $9.44 \times 10^6\,m^3$, the initial growing stocks are $2.43 \times 10^6\,m^3$ for larch forest (25.67%), $1.62 \times 10^6\,m^3$ for birch forest (17.17%), $3.16 \times 10^6\,m^3$ for mixed coniferous forest (33.46%), $2.02 \times 10^6\,m^3$ for mixed coniferous-broadleaf forest (21.37%), and $0.22 \times 10^6\,m^3$ for mixed broadleaf forest (2.30%). The age-class structure of the planning area is illustrated in Table 1.

2.2. Forest planning model

Forest ecosystems provide a wide range of goods and services, such as provisioning services (e.g., timber and nontimber products), regulating services (e.g., soil protection and water resources), cultural services (e.g., recreation and employment opportunities) and

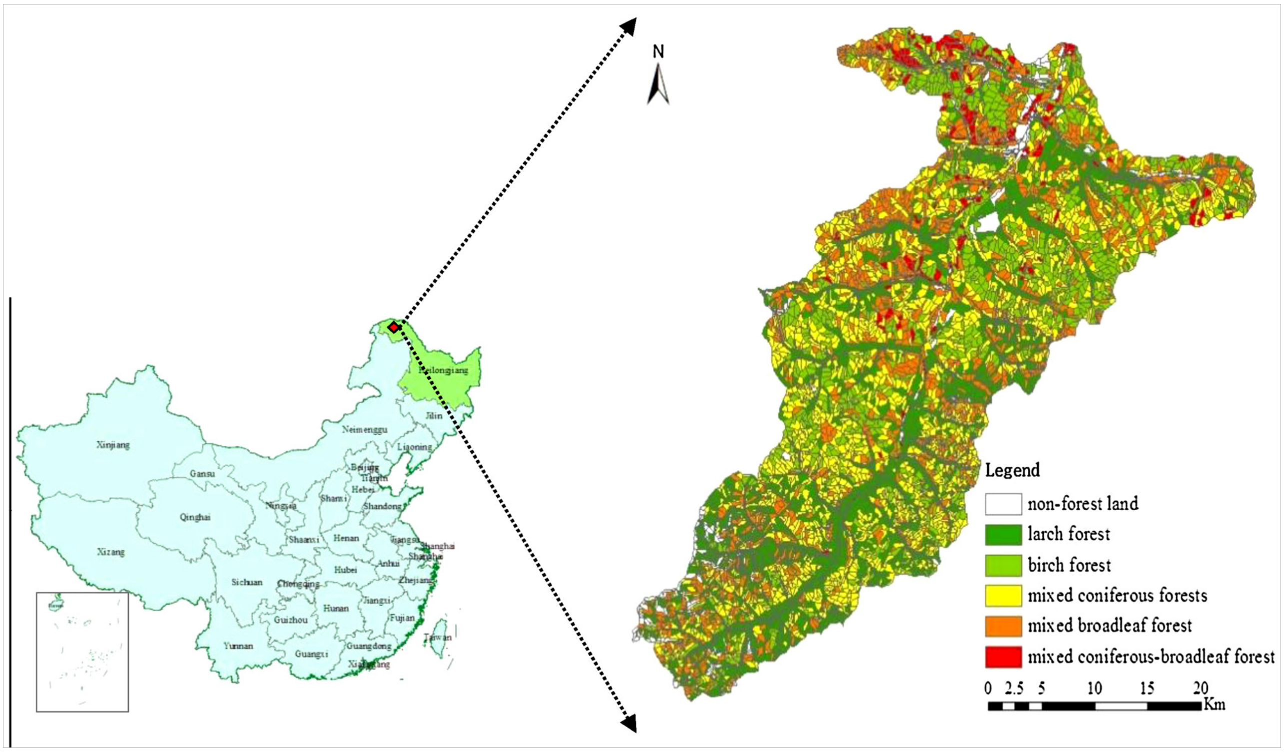

Fig. 1. The location of the study area in northeastern China.

supporting services (e.g., biodiversity and oxygen production). All these services are important for human well-being and environmental health; however, not all of these services can be quantitatively estimated in a way that is suitable for integration into the forest management planning process. Meanwhile, because of global climatic changes in recent decades, the current integration of carbon management objectives into the forest harvest scheduling process has drawn interest to novel goods and services provided by forest ecosystems in forest management practices. Thus, this analysis is focused only on forest timber production and carbon sequestration rather than on the incorporation of several other forest values.

2.2.1. Timber production

The development of forests was simulated using the standard stand-level growth and yield model system of Wang (2012), which consists of a site index, diameter increment, height increment, tree survival, basal area increment and volume models for all tree species in the study area (Fig. 2). The volumes of various timber products (i.e., sawlogs, mining pole and firewood) resulting from selective cutting at any age were determined by the available merchantable volume ratio tables (DB23/T 870-2004, 2004). The allocated proportion of various timber products was significantly different for different species, site qualities and mean stand diameters. The financial information associated with timber production included all revenues and costs from harvest activities, such as wood assortments revenues, logging costs and management costs. The prices of the various timber products of the five forest types were retrieved from the 2012 pricelist from the Forestry Department of Heilongjiang Province in Northeast China. The logging costs and management costs were estimated to be US\$ 9.08 per m^3 and \$4.54 per hectare for this analysis, respectively. All revenues and costs were discounted to NPVs using a 3% real discount rate as is generally applied to the financial analysis of forestry-related activities (Baskent and Keles, 2009; Dong et al., 2015a,b). Therefore, the formulations associated with timber production can be presented as:

$$HV_{tk} = \sum_{i=1}^{M} \sum_{j=1}^{N} P_{itk} \cdot (A_i \cdot V_{ijt} \cdot X_{ijt}) \quad \forall \text{t,k} \tag{1}$$

$$HV = \sum_{t=1}^{T} HV_t = \sum_{t=1=1}^{T} \sum_{k=1}^{K} HV_{tk} \tag{2}$$

$$PV_t^{timber} = \sum_{k=1}^{K} PV_{tk}^{timber} = \sum_{k=1}^{K} (\Pr_{itk} - Lc) \cdot HV_{tk} \quad \forall \text{t} \tag{3}$$

Table 1
Initial age-class structure of Pangu Forest Farm in northeastern China[a].

Age-class (year)	Forest types (ha)					
	Larch forest	Birch forest	Mixed coniferous forest	Mixed broadleaf forest	Mixed coniferous-broadleaf forest	Total
1–20	433	3,317	469	1,625	1,342	7,186
21–40	382	5,637	4,506	537	1,055	12,117
41–60	4,713	12,791	18,686	4,762	1,073	42,025
61–80	17,553	431	11,371	12,002	133	41,490
81–100	7,168		1,403	4,366		12,937
101–120	2,822		132	670		3,624
Total	33,071	22,176	36,567	23,962	3,603	119,379

[a] Refers only to the land covered by forest within the study area.

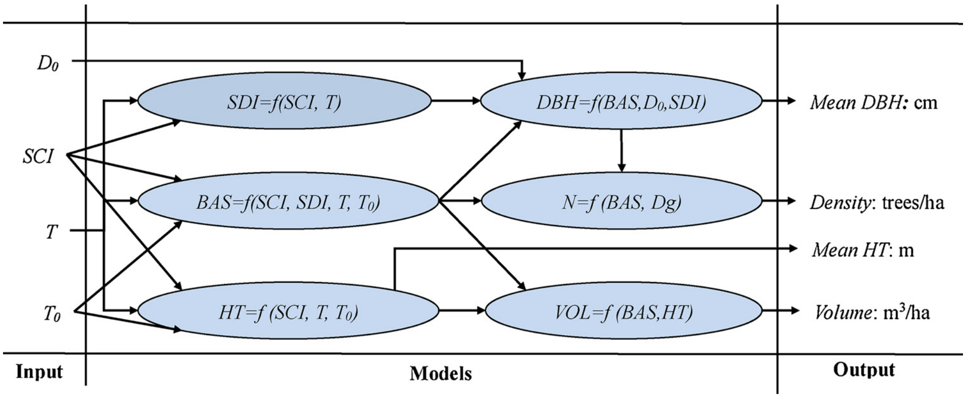

Fig. 2. Flow diagram of the stand-level growth and yield model system (Wang, 2012) in which T_0 and D_0 are the basal age and basal diameter at breast height (*DBH*), respectively, for specific forest stand types; *SCI* and *SDI* are the site class index and stand density index, respectively; *T*, *Dg*, *HT*, *N*, *BAS* and *VOL* are the stand age (year), mean DBH (cm), mean stand height (m), stand density (trees/ha), stand basal area (m^2/ha) and stand volume (m^3/ha), respectively.

$$NPV^{timber} = \sum_{t=1}^{T} \frac{PV_t^{timber}}{(1+p)^{(t-0.5)\cdot TPL}} \tag{4}$$

where M is the number of management units; i is an arbitrary harvest unit; N is the number of management prescriptions; j is an arbitrary management prescription; K is the number of wood products; k is an arbitrary wood production value containing the three wood products in this study, i.e., sawlogs, mining pole and firewood; A_i is the area of unit i; V_{ijt} is the harvested volume per hectare of unit i with prescription j in period t; and X_{ijt} is a binary variable indicating whether unit i is harvested with prescription j during time period t. Additionally, P_{itk} is the proportion of product k for unit i during time period t, which was different for different ages and mean diameters, even within the same unit; HV_{tk} is the total volume of product k in period t; HV_t is the total volume of all timber products for each time period; HV is the total harvested volume during the entire planning horizon; Lc is the logging cost per cubic meter volume; Pr_{ik} is the price of product k for unit i; PV_{tk}^{timber} is the total present value of product k in timber period t; PV_t^{timber} is the total present value of all products in time period t; TPL is the time period length; p is the discount rate in percentage; and NPV^{timber} is the total discounted NPV of timber production during the entire planning horizon.

Eq. (1) specifies the harvest accounting variables of product k from time period t (HV_{tk}). Eq. (2) first assigns the accounting variable HV_{tk} to the total harvest accounting variables of all timber products for period t (HV_t) and then aggregates the variable HV_t to form the total harvest accounting variables of all timber products (HV) during the entire time horizon. Eq. (3) first assigns the present value of product k from period t to the accounting variable PV_{tk}^{timber}, and then it calculates the total present value of all time products in time period t (PV_t^{timber}). Finally, Eq. (4) is used to sum the total discounted NPV of timber production during the entire time horizon (NPV^{timber}). As implemented here, all the revenues and costs associated with timber production would be discounted at the midpoint of each time period.

2.2.2. Carbon sequestration

The carbon stocks and sequestration values for the entire forest ecosystems are typically difficult to quantify, as the carbon flux process in forests might be influenced by various compartments, such as living forest biomass (e.g., trees, shrubs, and herbs), soil organic matter, and wood-based products (e.g., sawlogs, mining pole, and boards). Due to the enormous uncertainty and the significant spatial heterogeneity, as well as the inaccurate information about the soil layer and understory vegetation (i.e., shrub layer, herb layer and litter layer) of forest ecosystems, the carbon stocks of these compartments were not included in the calculations in this analysis. Additionally, the carbon stocks of various wood products were not considered in this paper, mainly due to a lack of suitable models and reliable data on the releasing process of wood carbon in our study area. Therefore, the biomass calculated here is related only to the above-ground and below-ground biomass of living trees with a DBH greater than 5 cm. The volume for each forest stand was calculated using the standard stand-level growth and yield model system (Wang, 2012), and the corresponding living tree biomass was estimated using a fixed biomass conversion factor of 0.8992 for larch forest, 0.9518 for birch forest, 0.7986 for mixed coniferous forest, 0.9284 for coniferous-broadleaf forest and 1.1389 for mixed broadleaf forest, which were determined using abundant anatomical trees across the entire region of northeastern China (Dong, 2015). The total dry weight biomass of a management unit was finally converted to total stored carbon by multiplying by 0.45. Therefore, the net carbon sequestration in successive periods may be estimated as the difference in the total remaining carbon stock on forestland between one period and the previous period. The financial value of carbon sequestration during the evaluated time horizon was determined by multiplying a carbon price with the amount of carbon sequestration in each time period, and the resulting value was discounted to the NPV using a real discount rate. The carbon price was applied to the whole planning horizon and was also fixed for the whole planning horizon. Thus, the formulations associated with carbon sequestration can be presented as:

$$CS_t = \sum_{i=1}^{M}\sum_{j=1}^{N} A_i \cdot C_{ijt} \cdot X_{ijt} \quad \forall t \tag{5}$$

$$\Delta_t = CS_t - CS_{t-1} \forall t \tag{6}$$

$$PV_t^{carbon} = P_c \cdot \Delta_t \quad \forall t \tag{7}$$

$$NPV^{carbon} = \sum_{t=1}^{T} \frac{PV_t^{carbon}}{(1+p)^{(t-0.5)\cdot TPL}} \tag{8}$$

where C_{ijt} represents the residual carbon stocks per hectare of unit i with prescription j in time period t; CS_t and CS_{t-1} are the amount of residual carbon stocks in time periods t and t-1, respectively; $\triangle_t$ denotes the amount of net carbon sequestration from time period t-1 to time period t; Pc is the price of carbon stock per ton; PV_t^{carbon} is the present value of net carbon sequestration in time period t; and NPV^{carbon} is the total discounted NPV of net carbon sequestration during the entire time horizon for the whole study area.

Eq. (5) comprises the residual carbon stock accounting variable (CS_t), which represents the total quantity of the carbon stock of the whole forestland in time period t. Eq. (6) represents the amount of net carbon sequestration during time period t ($\triangle_t$), namely, the difference in the total carbon stocks of the whole forestland from time period t to time period t-1. Eq. (7) is used to calculate the total present value of carbon sequestration in time period t (PV_t^{carbon}). Eq. (8) sums the total discounted NPV of carbon sequestration during the entire time horizon (NPV^{carbon}). Again, the revenues of carbon sequestration were also discounted using a 3% discount rate at the midpoint of each time period.

Table 2
An overview of various forest management planning scenarios.

Planning scenario	Objective	Carbon targets (10^6 ton)	Green-up constraints	Other constraints
C1	max NPV ^{carbon}			Eqs. (13)–(15)
C2	max NPV ^{carbon}			Eqs. (10), (13)–(15)
C3	max NPV ^{carbon}		0 periods	Eqs. (10), (12)–(15)
C4	max NPV ^{carbon}		2 periods	Eqs. (10), (12)–(15)
T1	max NPV ^{timber}			Eqs. (13)–(15)
T2	max NPV ^{timber}			Eqs. (10), (13)–(15)
T3	max NPV ^{timber}		0 periods	Eqs. (10), (12)–(15)
T4	max NPV ^{timber}		2 periods	Eqs. (10), (12)–(15)
M1	max NPV ^{timber} + NPV ^{carbon}			Eqs. (13)–(15)
M2	max NPV ^{timber} + NPV ^{carbon}			Eqs. (10), (13)–(15)
M3	max NPV ^{timber} + NPV ^{carbon}		0 periods	Eqs. (10), (12)–(15)
M4	max NPV ^{timber} + NPV ^{carbon}		2 periods	Eqs. (10), (12)–(15)
R1	max NPV ^{timber} + NPV ^{carbon}	CS* ≥ 1.26[a]	2 periods	Eqs. (10)–(15)
R2	max NPV ^{timber} + NPV ^{carbon}	CS* ≥ 1.58[b]	2 periods	Eqs. (10)–(15)
R3	max NPV ^{timber} + NPV ^{carbon}	CS* ≥ 1.90[c]	2 periods	Eqs. (10)–(15)
R4	max NPV ^{timber} + NPV ^{carbon}	CS* ≥ 2.20[d]	2 periods	Eqs. (10)–(15)

[a] The level in T4 + 20% of the difference between C4 and T4.
[b] The level in T4 + 40% of the difference between C4 and T4.
[c] The level in T4 + 60% of the difference between C4 and T4.
[d] The level in T4 + 80% of the difference between C4 and T4.

2.2.3. Planning formulation

The developed forest plans covered a 50-year time horizon that was divided into ten 5-year periods. The timber production and carbon sequestration of the forest ecosystems were both calculated at the stand level. The possible management prescriptions included three intensities of selective cutting treatments or the option to do nothing. The selective cutting treatments included low intensity (10%), middle intensity (20%) and high intensity (30%) harvest activities, which were all retrieved from the forest management policy of Heilongjiang Province in northeastern China. All treatments and the growth and yield projections of actual stands were assumed to occur at the midpoint of each period. The minimum age at which the selective cutting treatment was applied in natural larch forests, mixed coniferous forests and mixed coniferous-broadleaf forests was 60 years, and the minimum age for treatment in natural birch forests and mixed broadleaf forests was 40 years. Therefore, the management objective was to maximize the discounted NPVs of timber production and net carbon sequestration over the entire time horizon.

$$\text{Maximize } Z = \text{NPV}^{x} \tag{9}$$

subject to:

$$B_l HV_{t-1} \leq HV_t \leq B_h HV_{t+1} \quad \text{t=1, 2,}\cdots\text{,T-1} \tag{10}$$

$$\sum_{t=1}^{T} CS_t \geq CS* \tag{11}$$

$$A_i \cdot X_{ijt} + \sum_{k \in N_i \cup S_i} \sum_{m=1}^{T_m} A_k \cdot X_{kjm} \leq U_{\max} \quad \forall \text{ i} \tag{12}$$

$$\sum_{\text{i}}^{M} Age_{ijt} \geq Age_s^{\min} \quad \forall \text{t,j} \tag{13}$$

$$\sum_{t=1}^{T} X_{ijt} \leq 1 \quad \forall \text{i} \tag{14}$$

$$X_{ijt} \in \{0, 1\} \tag{15}$$

where Z is the objective function that indicates the sum of the cumulative NPV of the timber and carbon values in Eqs. (4) and (8), respectively; x is a variable that represents one of the timber and carbon values or the total summed value of timber and carbon; B_l is the lower bound on the decrease in harvest level from one period to the next; B_h is the upper bound on the increase in harvest level from one period to the next; $CS*$ represents the minimum target of the amount of carbon sequestration during the entire horizon; k is an arbitrary management unit that is either adjacent to unit i or adjacent to a management unit that is adjacent to unit i; N_i is the entire set of all management units adjacent to management unit i; S_i is the entire set of all management units adjacent to the set of management units (N_i) adjacent to management unit i, which were formulated in the form of a recursive function (Murray, 1999); t is an arbitrary time period; and T_m is the set of near-time periods, which represent the typical green-up constraints (Murray, 1999). For a 2-year green-up constraint, $T_m \in \{m_1 = t\text{-}2, m_2 = t\text{-}1, m_3 = t, m_4 = t + 1, m_5 = t + 2\}$, if $m_z < 0$, then $T_m = 0$, and if $m_z > T$, then $T_m = T$; $U_{\max}$ is the assumed maximum concurrent harvest area; Age_{ijt} is the stand age of management unit i when it was managed with prescription j in time period t; and Age_s^{min} is the minimum harvest age assumed for forest type s, in which s is a variable that represents one of the five forest types.

Eq. (9) specifies the objective function of this problem, i.e., to maximize the discounted NPV of the timber and carbon values during the entire time horizon. Eq. (10) restricts the deviation in harvest volume from one period to the next within an assumed proportion, i.e., 20% in this analysis. Eq. (11) indicates that the minimum carbon sequestration target identified for the planning horizon should not be violated. Eq. (12) represents the area restriction model of the adjacency constraints provided by Murray (1999). As implemented here, a slight modification of the original area restriction model was employed, i.e., the adjacency constraints focused only on the harvest time, mainly because the clear-cutting activities could not be utilized in this analysis. Eq. (13) limits the minimum thinning age for each unit. Eq. (14) prevents each management unit from being harvested more than once during the entire time horizon. Finally, Eq. (15) indicates that all decision variables should be binary, i.e., the arbitrary management unit should not be managed by two different management prescriptions throughout the entire planning horizon.

For testing purposes, four categorical planning procedures were generated from previous formulations as part of alternative management strategies (Table 2). The objectives of the first category (i.e., Scenarios C1–C4) were to maximize the cumulative NPV of carbon sequestration, referring to the carbon-oriented management strategy (CMS). The objectives of the second category (i.e., Scenarios T1–T4), referring to the timber-oriented management strategy (TMS), were to maximize the cumulative NPV of timber production. The objectives of the third category (i.e., Scenarios M1–M4), which represented the multiobjective forest management strategy (MMS), were to maximize the cumulative NPVs of timber production and carbon sequestration

together. These three categories should all be subjected to the base constraints (i.e., Eqs. (13)–(15)), the even-flow constraints of timber production (Eq. (10)), the green-up constraints with zero periods (i.e., Eq. (10)), and the green-up constraints with two periods (Eq. (10)). In addition to the three categories of constraints mentioned above, the planning objectives of the fourth category, referring to the resource-restricted management strategy (RMS), were to maximize the cumulative NPVs of timber production and carbon sequestration together; however, this category should be further subjected to the minimum carbon sequestration targets (i.e., Eq. (11)) that are typically specified by forest managers and decision makers. As implemented here, the minimum carbon sequestration targets were calculated as the level of carbon sequestration over the entire time horizon in Scenario T4 plus the percentages of the differences in carbon sequestration between Scenarios C4 and T4. The percentages were assumed to be 20%, 40%, 60%, and 80% in this analysis.

Since carbon prices have significant effects on the forest planning process (Backéus et al., 2006; Raymer et al., 2011), the effects of eight different levels of carbon prices (i.e., $0, $20, $60, $100, $200, $300, $400, and $500 per ton of carbon) on the forest planning in Scenario M4 were quantitatively evaluated. The value of $0 per ton of carbon reflects the present situation where the carbon objective has not been considered in forest management practices. The values of $20 and $60 per ton of carbon represent the realistic range of carbon prices in the Chinese market for carbon trading in 2014–2017. The values of $100, $200, $300, $400 and $500 per ton of carbon are some relatively higher carbon prices that have been employed in other scientific studies (Backéus et al., 2006).

2.3. Optimization technique

Due to the enormous complexity of the planning processes in our study, the satisfactory forest plan for each planning scenario was developed using a heuristic process called "simulated annealing", which is a scheduling process that was inspired by the cooling process of hot material (Fig. 3). Simulated annealing has been used to address a set of forestry planning problems. For example, Boston and Bettinger (1999), Crowe and Nelson (2005), and Pukkala and Kurttila (2005) used simulated annealing to solve the adjacency-restricted harvest scheduling problem; Öhman, Öhman (2011) used simulated annealing to model old-growth interior; Bettinger et al. (2002) used simulated annealing to schedule timber harvests subjected to wildlife habitat quality goals; Baskent and Jordan (2002) employed simulated annealing to maintain forest landscape structure; and Dong et al. (2015a,b) utilized simulated annealing to model the trade-offs between forest timber production and carbon sequestration. Though simulated annealing has certain substantive limitations that may be worrisome to some forest planners, this heuristic algorithm has been shown to provide very good solutions to various complex forest planning problems when compared to other commonly used heuristic algorithms (Bettinger et al., 2002; Pukkala and Kurttila, 2005), such as the Monte Carlo simulation, the tabu search, the threshold accepting method, and the genetic algorithm.

In forest resource management, the simulated annealing process begins with a feasible forest plan, which is generated either randomly or using a deterministic method. The simulated annealing search process then modifies the forest plan one aspect at a time, which is called a move. A move $N(S, m)$ of a solution S is a set of solutions that can be generated from S by a simple move m, i.e., randomly changing either harvest timing or prescription or randomly changing both of them simultaneously for just one unit in our scenario. To prevent the premature convergence to a local optimum, moves that improve the quality of the forest plan are always acceptable; however, non-improving moves may also be acceptable based on a probability:

$$p = \exp\left[\frac{(U_{new} - U_{old})}{T}\right] \tag{16}$$

where U_{new} is the objective function value of the proposed solution; U_{old} is the objective function value of the current solution; and T is the current temperature of the annealing process, which determines the probability of accepting nonimproving moves. Four parameters must be specified prior to using a simulated annealing algorithm: the initial temperature, the cooling rate, the number of iterations to be performed at each temperature and a stopping criterion (i.e., the final temperature). These parameters are usually case-specific, which is useful for determining how long the search process should be run. Therefore, arriving at an appropriate parameter set for a simulated annealing search process is always somewhat of an art. The trial-and-error method is one of the most commonly used approaches used to determine the appropriate parameter values for specific planning problems in the forestry literature (Boston and Bettinger, 1999; Strimbu and Paun, 2013). Based on a series of quantitative simulations, the appropriate parameter values for our planning problems were 10,000 degrees for the initial temperature, 10 degrees for the final temperature, 0.995 for cooling rate, and 300 iterations at each respective temperature; this process resulted in approximately 413,700 iterations per independent run.

The forest planning models that used the simulated annealing algorithm were encoded within the Microsoft Visual Basic 6.0 programming language. The solutions of each planning scenario were generated using a 2.6 GHz Core i5 CPU with 4 gigabytes of RAM and a Windows 7 Pro 32 bit operating system. To minimize the random effects of simulated annealing, ten feasible solutions were generated for each planning scenario from a random and feasible initial solution, while only the best solution for each scenario (i.e., the maximum objective function value) was selected and analyzed in this paper, as demonstrated in Bettinger et al. (2002), Strimbu and Paun (2013) and Dong et al. (2015a,b).

3. Results

3.1. Effects of carbon price on optimal management

The effects of carbon price on the optimal forest management plan were evaluated only for Scenario M4, in which the objective function was to maximize the joint discounted NPVs of timber production and carbon sequestration of the forest ecosystem using a 3% discounting rate (Table 3). The total NPV of the optimal management plan was $232.58 million when the carbon sequestration from the forest ecosystem was not considered as a source of income (when the carbon price of $0 ton^{-1} was employed). However, the total NPVs of the optimal joint plans reached $243.15 and $265.48 million, respectively, when the revenues from carbon sequestration were included with a realistic carbon price (i.e., $20 and $60 ton^{-1}). These values meant that revenues increased by approximately 4.54% and 14.15%, respectively, when compared to a carbon price of $0 ton^{-1}. Increasing the carbon price from $100 to $500 ton^{-1} further increased the revenues of the optimal management plans by about one to three times with respect to the plan with a carbon price of $0 ton^{-1}. The timber NPV with respect to the total NPV of the optimal management plan decreased significantly with the increases in carbon price, namely, decreasing from 100% when the carbon price was $0 ton^{-1} to 8.14% when the carbon price was $500 ton^{-1}; however, the carbon NPV and its percentage with respect to the total NPV of the optimal management plans both increased significantly. The NPVs of total and carbon can both be estimated using a quadratic polynomial, while the timber NPV should be estimated using an inverse logistic function, in which the determination coefficients (i.e., R^2) are all larger than 0.99.

The amount of produced timber, sequestered carbon and residual carbon stocks in the optimal management plans were almost the same when carbon prices ranged from $0 to $100 ton^{-1}. However, with the continued increases in carbon price (i.e., $200–$500 ton^{-1}), the amount of timber production in the optimal management plans significantly decreased, but the amount of carbon sequestration and

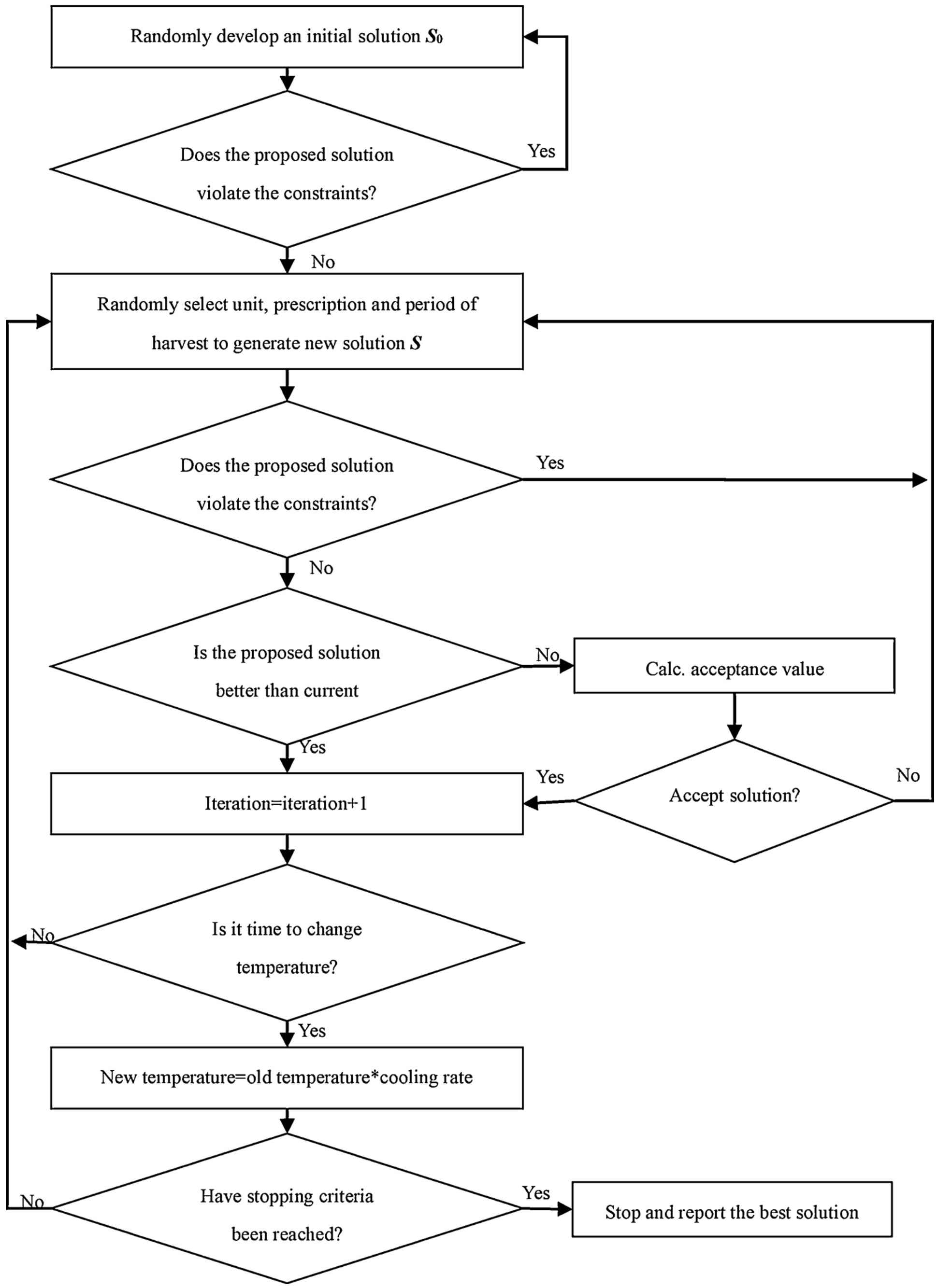

Fig. 3. Flow chart of the simulated annealing algorithm.

residual carbon stocks increased significantly. The abovementioned three variables can all be predicted using the logistic function, and the values of R^2 were as large as 0.95. When the carbon price was \$0 ton^{-1}, the assigned total harvest area was approximately 101.26 thousand hectares, which accounted for approximately 82.01% of the total forestland. Within this management plan, approximately 96.03% of the total harvest area was assigned with high-intensity thinning activities; however low-intensity and middle-intensity thinning activities accounted for only 0.94% and 4.29%, respectively. The assigned harvest area and their allocation patterns were almost the same when the carbon price was \$0 ton^{-1} and when the carbon prices varied from \$20 to \$100 ton^{-1}. The total assigned harvest area significantly decreased (i.e., 82.19 thousand hectares) when the carbon price was \$300 ton^{-1}, and the association patterns of the three thinning intensities were almost equal to each other. Increasing the carbon price to \$500 ton^{-1} further decreased the assigned harvest area, which accounted for only approximately 40.29% of the total forestland. In contrast to the optimal management plan with the carbon price of \$0 ton^{-1}, the percentage of low-intensity thinning within the optimal management plan when the carbon price was \$500 ton^{-1} was significantly larger than that of the high-intensity thinning activities. The harvest area of total and middle-intensity thinning can both be estimated using a quadratic polynomial (R^2 = 0.9974 and 0.8525, respectively), while the relationship between the harvest area and carbon price were respectively forward and inverse logistic functions for low (R^2 = 0.9978) and high (R^2 = 0.9942) intensity.

The amount of timber production and carbon sequestration in planning Scenario M4 over the time period and the various carbon prices are illustrated in Fig. 4. As expected, as the carbon price increased, the timber volume produced in each period distinctly

Table 3
Effects of carbon price on timber production and carbon sequestration in planning scenario M4 for Pangu Forest Farm over a 50-year time horizon.

Variable	Carbon price ($US ton^{-1})							Predictive model	
	$0 ton^{-1}	$20 ton^{-1}	$60 ton^{-1}	$100 ton^{-1}	$200 ton^{-1}	$300 ton^{-1}	$400 ton^{-1}	$500 ton^{-1}	Function	R^2
NPV ($ 10^6)	232.58	243.15	265.48	292.39	378.74	489.79	614.40	746.87	$Y = 0.0009x^2 + 0.5776x + 229.48$	0.9996
NPV of timber ($ 10^6)	232.58	233.72	235.71	232.82	190.52	135.29	90.48	60.83	$Y = 260.076/(1 + 0.080^{a}\exp(0.776^{a}\ x/100))$	0.9902
NPV of carbon ($ 10^6)	0.00	9.42	29.77	59.57	188.21	354.50	523.92	686.03	$Y = 0.0012x^2 + 0.8106x - 14.014$	0.9970
Timber production (10^6 m^3)	3.17	3.17	3.21	3.19	2.57	1.89	1.29	0.87	$Y = 3.560/(1 + 0.086^{a}\exp(0.745^{a}\ x/100))$	0.9890
Carbon sequestration (10^6 ton)	0.93	0.95	0.96	1.09	1.71	2.11	2.34	2.46	$Y = 2.722/(1 + 2.341^{a}\exp(-0.655^{a}\ x/100))$	0.9830
Carbon stocks (10^6 ton)	5.24	5.27	5.27	5.40	6.02	6.42	6.65	6.77	$Y = 7.724/(1 + 0.509^{a}\exp(-0.275^{a}\ x/100))$	0.9730
Thinning area (10^3 ha)	101.26	101.08	101.48	100.47	93.18	82.19	65.61	49.73	$Y = -0.0002x^2 - 0.0045x + 101.88$	0.9974
Low-intensity (10^3 ha)	0.94	1.07	1.00	1.81	10.62	22.52	29.13	28.50	$Y = 29.37/(1 + 78.01^{a}\exp(-1.88^{a}\ x/100))$	0.9978
Middle-intensity (10^3 ha)	4.29	3.38	4.12	8.29	33.51	39.56	28.63	18.37	$Y = -0.0004x^2 + 0.2381x - 2.6339$	0.8525
High-intensity (10^3 ha)	96.03	96.64	96.36	90.37	49.05	20.12	7.86	2.86	$Y = 103.499/(1 + 0.042^{a}\exp(1.562^{a}\ x/100))$	0.9942

[a] The basic *Logistic* function is $Y = a/(1 + b^{*}\mathrm{Exp}(-c^{*}x))$, in which x and Y are the independent and dependent variables, respectively, and a-c are the estimated parameters; R^2 represents the determination coefficients of the fitted models.

decreased. However, the differences in the amount of harvested timber in each period were not significant when the carbon prices varied from $0 to $100 ton^{-1}. As the carbon price gradually increased, the assigned harvested timber of each period decreased significantly compared with the harvest when the carbon price was assumed to be $0 ton^{-1}. In all analyses of the carbon prices, the assigned harvests of timber for each period were all subjected to the even-flow (of harvest volume) objective [in Eq. (10)]. For carbon objectives, the differences in the amount of carbon sequestration in each period were also not significant when the carbon prices varied from $0 to $100 ton^{-1}; however, significant declining trends in the amounts of carbon sequestration were observed over the time periods when the carbon price ranged from $200 to $500 ton^{-1}. The quantity of carbon sequestration in the first period of each 50-year planning plan was approximately three times larger than that in the last period for all of the higher carbon prices.

3.2. Effects of various constraints on optimal management

The effects of various constraints on the optimal management plans were evaluated for all alternative forest management scenarios in Table 2 using a realistic carbon price (i.e., $20 ton^{-1}) for carbon trading in the Chinese market during 2014–2017. The NPVs of the total, timber and carbon of the sixteen alternative forest management scenarios are illustrated in Fig. 5. The differences in the NPV of the total, timber and carbon components for Scenarios C1 through C4 were all difficult to distinguish when the carbon revenues were maximized individually. For the timber production objectives (T1–T4), Scenario T1 produced a higher NPV of total revenues than did the other scenarios over the planning horizon. The even-flow constraints of harvest volume (i.e., Scenario T2) had a significant negative effect on the total NPV when compared to that of Scenario T1, with the output reduced by approximately 29.34%. The adjacency constraints (i.e., Scenario T3) had no significant effects on the optimal

management plans when compared with those of Scenario T2, and this was primarily because larger openings were used in this analysis. However, the total NPV of the optimal management plans decreased significantly (17.87%) when the green-up constraints (i.e., Scenario T4) were further incorporated into Scenario T3. The changes in the total NPV in the MMS (i.e., Scenarios M1–M4) were perfectly consistent with those in the TMS (i.e., Scenarios T1–T4), mainly due to the relatively low carbon price (i.e., $20 ton^{-1}) employed in the planning processes. However, the responses of carbon NPV to various constraints showed obvious opposite trends with respect to the TMS (i.e., Scenarios T1–T4) and MMS (i.e., Scenarios M1–M4). As expected, as the minimum carbon target increased, the NPV of the produced timber decreased; however, increases in the NPV of carbon were generated when the minimum carbon sequestration targets were incorporated into Scenario M4. As emphasized here, all revenues of timber and carbon objectives were profitable in the planning scenarios except for the carbon benefits in Scenarios T1 and M1, which indicated that an unreasonable amount of timber was harvested under these planning scenarios during the planning horizon.

The amount of timber production, carbon sequestration and carbon stocks of the various forest management strategies shown in Fig. 5 further verified the conclusions from an economic perspective. When carbon revenues were the unique management objective, the various constraints (i.e., Scenarios C1–C4) had no significant effects on the optimal management plans. Scenarios T3 and M3 produced more timber than did the other scenarios over the planning horizon, while the amounts of timber produced in Scenarios T4 and M4 were the lowest when evaluated for the TMS (i.e., Scenarios T1–T4) and MMS (i.e., Scenarios M1–M4). The values of carbon sequestration over the planning horizon all demonstrated significant increasing trends as the complexity of the planning formulations increased; in contrast, the carbon stocks had no significant increasing trend, except for Scenarios T4 and M4. As the minimum carbon sequestration target increased, the

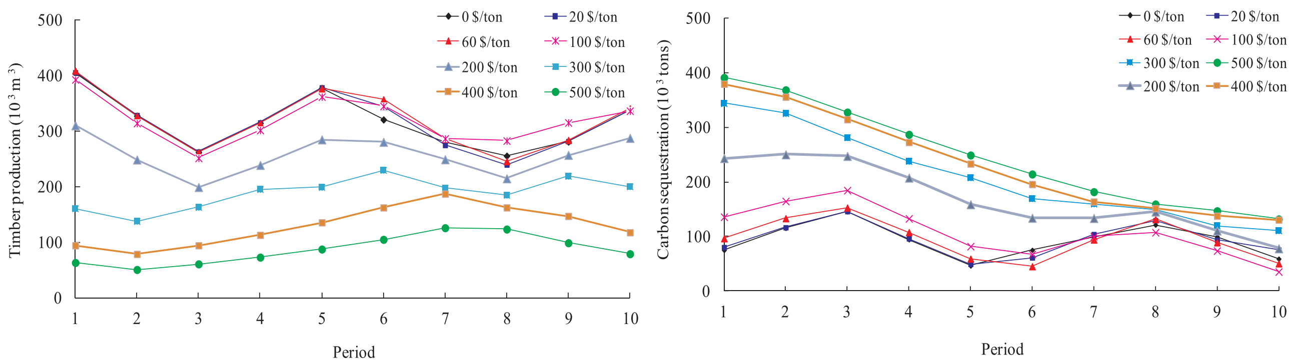

Fig. 4. Effects of different carbon prices on timber production (left panel) and carbon sequestration (right panel) of planning Scenario M4 over the time period.

amount of timber production decreased significantly; however, the quantities of carbon sequestration and residual carbon stocks both significantly increased when evaluated for planning Scenarios R1–R4.

The changes in timber production and carbon sequestration over time periods for the alternative forest management strategies are shown in Fig. 6. The amount of timber production for the CMS (i.e., Scenarios C1–C4) showed a gradual increasing trend over the time periods; in contrast, the amount of carbon sequestration decreased significantly for Scenarios C1–C4. As emphasized here, the differences in timber production and carbon sequestration in the CMS (i.e., Scenarios C1–C4) were all not significant over the evaluated time periods. For the TMS, the amount of timber production in Scenario T1 decreased significantly over the time periods; specifically, the harvest volume in the first period was approximately 2377.33 thousand m^3, but the harvest volume in the last period was only approximately 0.30 thousand m^3. As expected, the amount of carbon sequestered in Scenario T1 increased significantly over the time periods, from −1576.57 to 287.88 thousand tons. However, the timber production and carbon sequestration values were almost the same for the optimal forest management plans of Scenarios T2 and T3, which was mainly due to the larger openings that were used. Scenario T4 usually produced less timber in the first period but had approximately equal timber in the latter periods when compared with Scenarios T2 and T3. The amount of carbon sequestration in Scenario T4 showed significant opposite trends. Again, the changes in timber production and carbon sequestration in the MMS (i.e., Scenarios M1–M4) were all almost the same as the values in the TMS (i.e., Scenarios T1–T4). Finally, the changes in timber production for Scenarios R1 through R4 were all not evident over the evaluated time periods; however, the carbon sequestration decreased significantly over the time periods, except for Scenarios R1 and R2. In addition, the amount of timber production within each period decreased dramatically for Scenarios R1–R4, i.e., when the minimum carbon sequestration targets were used and increased, but the amount of carbon sequestration significantly increased. Larger differences for carbon sequestration were observed in the first period (i.e., approximately 189.94 thousand tons in the first period), but the differences decreased significantly in the later periods (i.e., approximately 32.23 thousand tons in the last period).

4. Discussions

This study formulated a spatially explicit forest management planning model that incorporated carbon objectives into traditional forest harvest scheduling processes. The effects of various carbon prices, economic constraints and ecological constraints were quantitatively evaluated for certain alternative forest management strategies. The results of the model outputs showed that increasing the amount of carbon sequestration can be attained at a significant cost in terms of forgone timber production and revenue returns. Similar results were also found in Backéus et al. (2006), Baskent and Keles (2009), Baskent et al. (2011), and Raymer et al. (2011). Therefore, if forest management

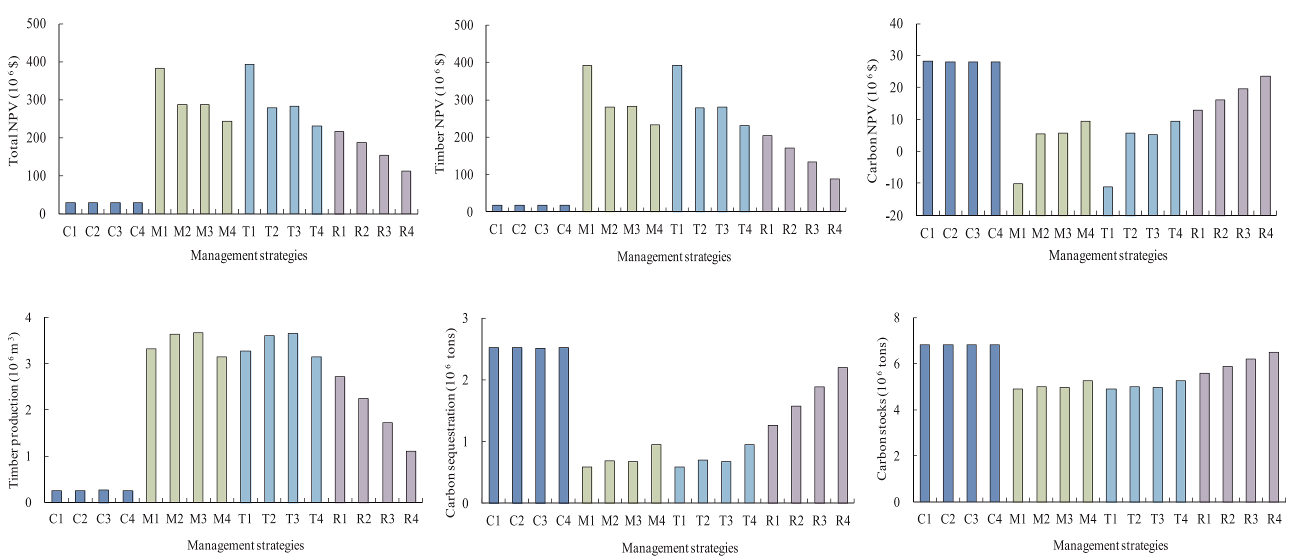

Fig. 5. The NPVs (first row) and the qualities (second row) of timber production, carbon sequestration and carbon stocks of various forest management strategies, in which the symbols *C*, *M*, *T*, and *R* represent the carbon-oriented management strategy, the multiobjective management strategy, the timber-oriented management strategy, and the resource-restricted management strategy, respectively, and the numbers 1–4 represent the different combinations of alternative constraints shown in Table 2.

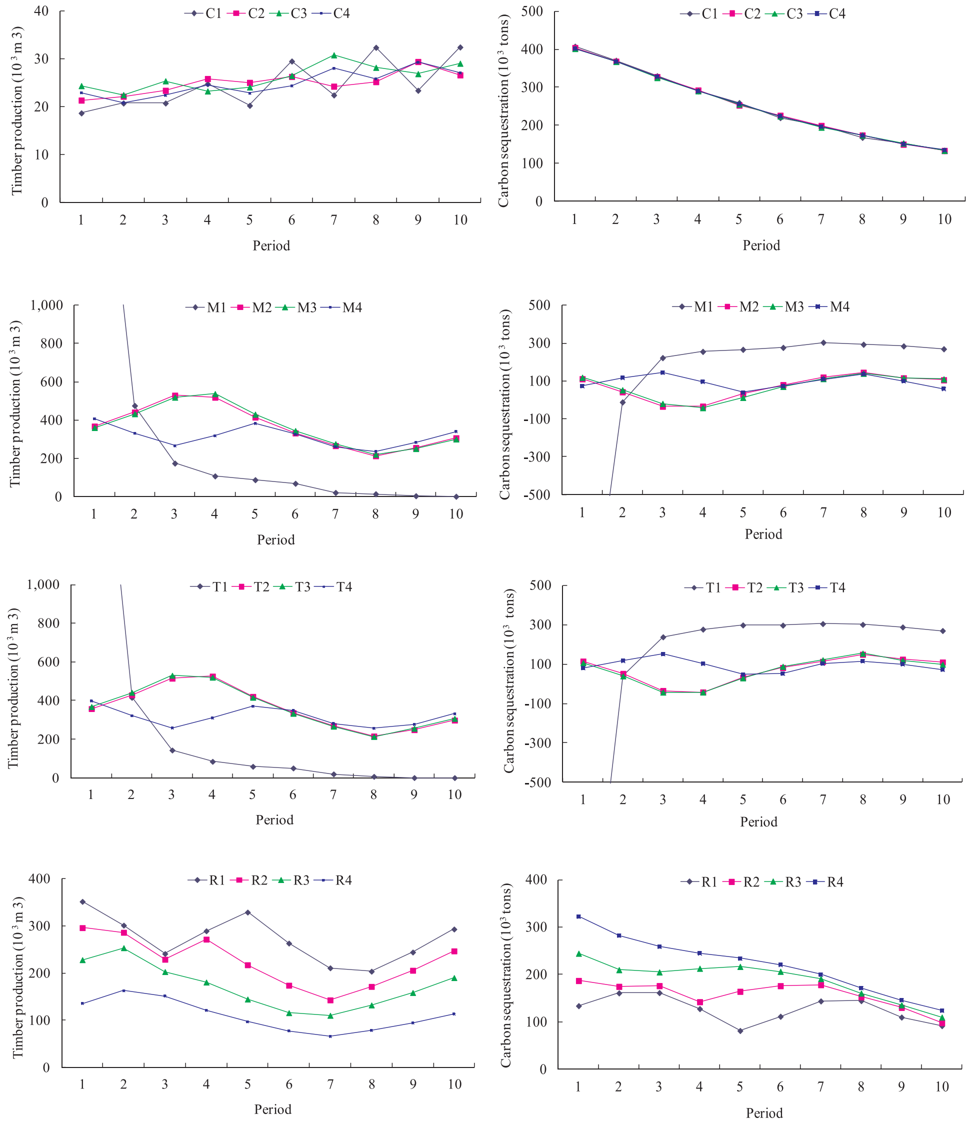

Fig. 6. Effects of various constraints on timber production (left panel) and carbon sequestration (right panel) over the time period for alternative forest management strategies, in which the symbols *C*, *M*, *T*, and *R* represent the carbon-oriented management strategy, the multiobjective management strategy, the timber-oriented management strategy, and the resource-restricted management strategy, respectively, and the numbers 1–4 represent the different combination forms of alternative constraints shown in Table 2.

organizations can alter or adjust their forest management policies, such as from a TMS to a MMS, they should evaluate the potential revenues and costs of these management strategies as well as the necessary constraints, as demonstrated in this paper.

The unit monetary values of carbon are a critical financial economic factor that not only affects the revenues of optimal management plans but also has significant effects on the amount of timber production and carbon sequestration over the planning horizon. Clearly, for long-term forest management planning in northeastern China, increasing the carbon price from \$0 to \$500 ton^{-1} significantly increased the amount of carbon sequestration; however, this practice also had dramatically negative effects on timber production in the optimal management plans. The threshold value that affected the balance between harvesting timber and keeping trees to sequester carbon was estimated to be \$100 per ton; however this might be somewhat overestimated when compared with realistic carbon prices, mainly because 1) not all the components of carbon sequestration related to forests and forestry were included, which leads to an overestimation of carbon price when using an optimization technique; 2) some uncertainty factors in the optimal management plans were not included for such large and lengthy planning efforts; 3) some subsidies from the central and local government for management (i.e., forest tending projects) and protection (i.e., natural forest protection projects) of forest resources were also not considered. From the perspective of optimization, if a wide range of carbon prices can be evaluated as implemented in Backéus et al. (2006), Raymer et al. (2011) and Qin et al. (2017), then the amount of carbon sequestered can be treated as a dependent variable, while the price of carbon can be treated as an independent variable, and their relations can then be understood using a linear or nonlinear function, which may be more practical in forest management practices. However, this method is of course an empirical result and is impossible to utilize in other regions; thus, the intrinsic mechanism regarding the trade-offs between carbon price and carbon sequestration still requires further research efforts. Meanwhile, all the price parameters (including carbon and timber prices) used in this analysis were deterministic. However, the introduction of a carbon price would affect the other prices in reality, such as timber prices, logging costs, and discounting rates. If one were to assume that the dynamics of all these prices would be utilized in the planning process, then the methodology in this paper could relatively easily be reinforced by incorporating the adaptive

prediction models of various prices into the model structure as constraints. However, we must leave this area of investigation for future research efforts, mainly due to the lack of necessary predictive models for prices in this region.

The harvest volume flow constraints are inherent parts of any harvest scheduling model around the world (e.g., Boston and Bettinger, 1999; Murray, 1999; Seidl et al., 2007; Öhman, 2011; Dong et al., 2015a,b), and these constraints are often recognized as important to forest product industries to ensure the full utilization of equipment and labor (Martins et al., 2014). The results of our forest management scenarios showed that the impacts of even-flow constraints on timber production were all significant, with the reductions in timber NPV being as large as 29.34% and 25.08% for the TMS and MMS, respectively, when the even-flow constraints (Eq. (10)) were incorporated into the planning formulations. This result was perfectly in line with that from the study by Baskent and Keles (2009), in which the NPV of revenues decreased by approximately 24.08% when the even-flow objective was considered. However, a slight increasing trend (i.e., approximately 5.10%) was observed for the CMS, mainly because the amount of timber production under this management strategy was much lower than those of the other management strategies (i.e., by an average of 9.13% in the harvest levels under other strategies); thus, the limitations of even-flow on the optimal management plans caused fluctuations. However, the main drawback of developing a forest plan with an even-flow objective is that the harvest level in one time period can limit the harvest levels in all the other time periods (Bettinger et al., 2007); the reason for this may be that the harvest patterns of timber production are highly dependent on the initial landscape conditions, such as the age-class distribution, stand density and site quality. For example, the harvest levels in older forests were usually significantly greater than those in younger forests (Zhu and Bettinger, 2008). As emphasized here, the abovementioned studies analyzed only the trade-offs between the even-flow of harvest timber and economic maximization from the perspective of wood supply capacity from forest ecosystems, while ignoring the importance of demand from the wood market. In forestry, Johnson and Scheurman (1997) have suggested numerous techniques for optimizing timber harvest and investment in public and private forests managed on an even-aged basis. Therefore, if the demand for timber from the wood market can be estimated in advance, then this demand could be further employed in place of the even-flow of timber requirements, which might be more meaningful from the perspective of forest management practice.

Spatial restrictions on the location and timing of harvest activities play an important role in maintaining the stability of landscape structures and the diversity of forest ecosystem services. Therefore, spatial restrictions have become increasingly important, mainly due to the recent developments in forest management regulations (e.g., Boston and Bettinger, 2006) and forest certification programs (e.g., Sustainable Forestry Initiative, 2015). Harvest adjacency and green-up constraints are the most commonly used spatial restriction types in the forestry literature. Many studies have shown that increasing the assumed maximum opening size or decreasing the green-up periods may be economically beneficial; however, these actions may also intensify the processes of landscapes or wildlife habitats fragmenting (e.g., Boston and Bettinger, 2006; Martins et al., 2014; Borges et al., 2015; Dong et al., 2015a,b). In this larger modeling effort, the negative effects of adjacency constraints (i.e., the green-up constraints with zero period) on the optimal management plans were all not significant; in contrast, approximately 5.10%, 0.40% and 1.31% increases in the total NPV were observed for the CMS, TMS and MMS, respectively. The reasons for this result may be that 1) the average size of management units (approximately 19.15 ± 10.80 ha) across the forest landscape was very different from the assumed maximum opening area (i.e., 40 ha) in this analysis, and 2) the set of possible choices (i.e., 30 potential management prescriptions) for each forest stand was much greater than other planning instances; thus, the limitations of the adjacency constraints on the harvest activities might not be as strict as those implemented in other studies, such as those by Crowe and Nelson (2005), Boston and Bettinger (2006), and Tóth et al. (2013). However, our results from Figs. 5 and 6 further indicated that increasing the length of green-up constraints from 0 to 2 periods had significant effects on the optimal management plans, and the reductions in the total NPVs were approximately 4.48%, 17.87% and 15.73% for the CMS, TMS and MMS, respectively.

Resource restrictions in forest ecosystems usually play very decisive roles in terms of carbon sequestration. The reason for this may be that some of the forest stands have previously been protected to meet carbon objectives rather than be harvested for timber. As expected, the optimal forest management plans gradually changed toward lower harvesting values and increased protection values as the restrictions imposed by the minimum carbon objective increased. The NPV of the optimal management plans of the RMS (i.e., Scenarios R1–R4) would be significantly decreased by an average of approximately 29.44 $\$/(ha^{-1}\,yr^{-1})$ if the minimum carbon target was increased by only one percent. This result also corresponded to a decrease of approximately $0.45\,m^3/(ha^{-1}\,yr^{-1})$ in timber production and an increase of approximately $0.26\,ton/(ha^{-1}\,yr^{-1})$ in carbon sequestration for the optimal forest management plans. Similar results were also reported in a study by Keleş and Başkent (2007), in which a decrease in timber of approximately $5.23\,m^3/(ha^{-1}\,yr^{-1})$ and an increase in carbon of approximately $1.06\,ton/(ha^{-1}\,yr^{-1})$ were observed when the minimum carbon target was increased by one percent. Obviously, the magnitude of the increases in timber and the decreases in carbon are highly dependent on the planning strategies that are implemented.

For spatially explicit forest management planning problems, which are typically formulated based on Model I of Johnson and Scheurman (1997), it is well known that this kind of planning problem can be solved with normal linear programming tools (e.g., GLPK, CBC, CPLEX, GUROBI or LINGO) when the problem sizes are limited. However, some enhanced techniques, such as the generalized management units formulation, the bucket formulation, the path formulation, and the cluster packing formulation (Tóth et al., 2013), might be more helpful to mitigate their disadvantages of being time consuming and not good at handling the spatial constraints of harvest activities when the planning problem sizes become very large, as implemented in this paper (i.e., 6421 units, 10 periods, 4 potential prescriptions). However, we also must admit that spatial problems are still difficult to formulate, and solvers can require considerable time to process, as these issues highly depend on the size and the complexity of planning problems. Meanwhile, many previously studies have confirmed that the precision of simulated annealing can meet the requirements of forest management very well (e.g., Boston and Bettinger, 1999; Bettinger et al., 2002; Pukkala and Kurttila, 2005), even when compared with the results from relaxed (i.e., ignoring the spatial constraints) linear programming. Boston and Bettinger (1999), for an example, reported that simulated annealing found the highest solution value for three of the four planning problems with different age-class structures and were all less than 4% from the objective function values of relaxed linear programming. Therefore, the robust simulated annealing algorithm was employed to solve our planning problem. The coefficients of variation of the ten objective function values for each planning scenario only varied from 3.71% to 13.98%, indicating relatively higher stability of the results from simulated annealing when using a self-validation process that recommended by Bettinger et al (2009). However, some improved heuristic algorithms (including simulated annealing), such as the neighborhood search (Dong et al., 2015a,b), hybrid search (Li et al., 2010), and revision search (Bettinger et al., 2015), are all promising for improving the optimization ability. In addition, a relatively outmoded programming language (i.e., Visual Basic 6.0) was employed in this paper; thus, attempting to utilize other advanced programming languages (e.g., c#, vb.net) may substantially shorten the optimization time.

A final point of discussion is that not all the components of carbon sequestration related to forests and forestry were included, such as the carbon in the understory vegetation, litter and soil levels in the forest ecosystem, and carbon in the wood products in the forestry market. In the field of forestry, Backéus et al. (2006), Baskent and Keles (2009) and Baskent et al. (2011) have successfully incorporated the carbon components of various wood products into the planning process using strategies related to the lifetime of wood products; Seidl et al. (2007) and Bottalico et al. (2016) incorporated almost all the carbon components of forests and forestry in a framework of multipurpose forest management planning using certain process-based, stand-level estimators, such as the 3-PG and InVEST models. These valuable publications are all beneficial and promote the development of forest management planning. However, the applicability of these models has not been verified in our study area, and some parameters within these models should be calibrated using our experimental datasets. In addition, removing nutrients (e.g., stemwood) and reducing organic matter inputs into forest soils through different harvesting intensities may affect long-term forest soil fertility and stand productivity (Mack et al., 2014), in turn affecting the carbon sink capacity of forest ecosystems, especially on sites with coarse-textured soils and low soil organic matter (Powers et al., 2005). However, this feedback is still difficult to quantify using mathematical formulas, and it is currently impossible to integrate this relationship into the forest management planning process.

5. Conclusions

This paper focused on a single forest area in northeastern China, and the study was limited to only two forest values rather than incorporating many other forest values (e.g., water, soil, biodiversity). However, it was sufficiently effective to illustrate the effects of a set of tested economic and ecological constraints on alternative forest management strategies. The prices of carbon had significant nonlinear effects on the economic benefits and the amount of timber production and carbon sequestration when evaluated for scenario M4 using a 3% discounting rate, in which increasing the prices of carbon from 0 to \$500 per ton resulted in positive quadratic polynomial total and carbon NPVs (R^2 = 0.9996 and 0.9970), positive logistic carbon sequestration and stocks (R^2 = 0.9830 and 0.9730), and negative logistic harvest of timber and its NPV (R^2 = 0.9890 and 0.9902) for optimal forest management plans. The carbon price of \$100 per ton was found to be a significant threshold for balancing the harvest of timber and carbon sequestration.

In addition to the CMS, our tested spatial and nonspatial constraints all showed significant effects on optimal forest management plans when a realistic carbon price (i.e., \$20 ton^{-1}) from the carbon trading market in China during 2014–2017 was employed, in which decreases of approximately 29.34% and 25.08% were observed for the total NPV when twenty percent deviations in assigned harvest volume between any two consecutive periods were employed. Additionally, two periods of green-up constraints can further reduce the total NPV by approximately 17.87% and 15.73% for TMS and MMS, respectively, when compared with their base scenarios. However, increasing the minimum carbon target by one percent reduced the total NPV by approximately 29.44 \$/($\text{ha}^{-1}\,\text{yr}^{-1}$) when evaluated for the RMS. Therefore, the importance of evaluating the trade-offs between forest economic benefits and ecological protections cannot be overemphasized for forest managers.

The above results are obviously strongly tied to the particularities of the study area, although it is possible to transfer and implement our optimization framework in other regions when the necessary elements (e.g., forest growth and yield models, price parameters of various products) are adequate. However, the effects of some uncertainties on the optimal management plans, such as climatic changes, unpredictable events (e.g., wind damage, fire hazard, and insect injury), and the intentions of decision makers, may affect the applicability, and these have been left for future research efforts.

Acknowledgments

This study was financially supported by the National Key Point Research and Development Program of China [grant number 2017YFC0504103] and the National Natural Science Foundation of China (31700562). We would also like to thank the two anonymous reviewers for their valuable comments and suggestions on this paper.

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